Submission to the

Encyclopedia of Planetary Sciences and Astrogeology

Entry Title: **EPHEMERIDES**

Author: X. X. (Skip) Newhall

Jet Propulsion Laboratory, M/S 238-332
California Institute of Technology
Pasadena, CA 91109-8099

Phone: (818) 354.0000
Fax: (818) 393-6890

(1)

THE ENCYCLOPEDIA OF PLANETARY SCIENCES AND ASTROGEOLOGY

a forthcoming volume in the
ENCYCLOPEDIA OF EARTH SCIENCES SERIES
Series Editor: Rhodes W. Fairbridge

Preliminary Information Sheet
January 1991

Editors:

James H. Shirley
Post Office Box 169
Canoga Park, CA 91305
Tel. 818-888-7631
jhs@pinet.aip.org

Rhodes W. Fairbridge
Department of Geological Sciences
Columbia University
New York, N. Y. 10027 USA
Tel. ?l?-( )()3-8793

Format

The Encyclopedia of Planetary Sciences and Astrogeology will have the same general format as other volumes in the Encyclopedia of Earth Sciences Series (published by Van Nostrand Reinhold, New York). It will have a preface/introduction by the editors, a list of contributors (names and institutional addresses), encyclopedia entries arranged in alphabetical order (each entry will be signed by the author and include its own bibliography), internal cross-referencing among articles, and a comprehensive index covering the entire volume.

The finished volume will be approximately ‘/00 pages in length, in a 6 ‘//8 by 10 inch format, providing about 800 words per page. A limited number of color illustrations and photographs will be included.

There will be three general categories of articles. The most significant topics will be discussed in articles of up to 5000 words in length. A second category of specialized topics will receive articles of 1000 -?000 words. The third category of entries consists of definitions of up to 500 words.

Content and Style

The readership of this series consists primarily of academics (both faculty and students) and professionals, including scientists from other disciplines. These volumes are also used by libraries and information centers to answer general inquiries. Therefore, whereas articles for this particular volume should be written to be useful to professional planetary scientists, they must also be accessible to those whose expertise lies in other areas.

We wish to treat all of the planets and the principal moons in a consistent fashion. The sections for each planet will include discussions of the planetary magnetic field, atmosphere, interior, and surface (where appropriate). Each of these topics may be treated by separate contributors; alternatively one individual may author several entries where appropriate.

Much new information concerning Venus, the Neptune system, and comet Halley has recently become available. The smaller bodies of the solar system (comets and asteroids) are likewise the object of considerable research at present. An encyclopedia is not an appropriate forum for the first presentation of new data or untested theories; however we wish to incorporate as much new information as is practicable in this volume. We will attempt to give equal time to both sides of major unresolved questions, such as the origins of the iridium anomaly at the KT boundary. We would like to emphasize *processes*, such as accretion, impact cratering, mantle convection, and volcanism, in the context of "comparative planetology."

We do not want to de-emphasize or neglect theoretical aspects. Important theories which have gained wide acceptance should be included in the volume. However, space limitations and the audience profile set constraints. Exhaustive, comprehensive treatments of theories cannot be included, but summaries may be appropriate.

Articles should follow an encyclopedia format, beginning with introductory material and progressing to more advanced concepts and phenomena. The historical development of the topic is often of interest, but this should not be emphasized over current knowledge and applications. Fundamental equations are appropriate if they are not lengthy and involved; if so then the appropriate sources should be cited in the bibliography.

Illustrations

Contributors will be responsible for preparing their own illustrations (if this is a problem, please contact the editors). We expect that most of the illustrations will consist of line drawings, graphs, charts, and black and white photographs. **A** limited number of color photographs will be included, possibly in a series including multiple views of each major body.

Bibliographic References

The longest articles may include up to fifty references, while definitions should include about five or fewer,. The references should enable the reader to begin a more in-depth investigation of the topic. Important references and more comprehensive review articles should be included, but the bibliography itself need not be coil-llJJellcllsi\~c. In typing references, contributors should include as complete bibliographic information as possible (abbreviated title of journal, number of pages in a book or *monograph*) and the editors will standardize the format for reference citation throughout the volume. Do not use footnotes 01 numbered references. Acknowledgements are inappropriate in an encyclopedia unless they are essential for NSF grants, etc.

Contributors

We are currently soliciting authors to write articles and entries for the Encyclopedia of Planetary Science and Astrogeology. **Please'** let us know what articles you might be willing to contribute, or if you have colleagues that you would suggest as potential contributors. We encourage the use **of** co-authors in writing the major articles. In some cases it may be most efficient if the same person writes a group of related articles (for instance, describing the atmospheric circulations of two or more of the gas giants). We hope to receive contributions from investigators from many different countries and institutions, to ensure a broad perspective.

Wc Heed help in reviewing and evaluating articles; if you would be willing to contribute in Ibis capacity, please let us know.

Once you have informed us of your interest in contributing to this volume, we **will discuss** with you the nature of your particular contribution(s) and send you

EPHEMERIDES

An ephemeris (plural: ephemerides, pronounced Eff-uh-MEHR-i-Deez) is defined to be a tabular listing of the position of a celestial body at regular intervals. Throughout history scientifically observant cultures have sought to understand and predict celestial phenomena, most notably the motions of the Sun, Moon, and planets.

Any effort to establish an ephemeris involves the development of some sort of mathematical model which reproduces past and current observations. This model is then evaluated at regular extrapolated intervals to obtain the desired predicted positions. The models devised by ancient astronomers consisted of elaborate systems of what were termed epicycles, wherein the Sun and planets were attached to a hierarchy of circles. The center of each of these circles rode on another circle, and the entire system ultimately was assumed to have the Earth as its center. Despite this unwieldy complexity the system described celestial motions with fair success over short periods, though it was unworkable over long time spans.

In the renaissance the invention of the telescope, the rise of mathematics, and Isaac Newton's theory of universal gravitation] established celestial mechanics as a respectable scientific endeavor. Kepler deduced that planets follow elliptical orbits with the Sun at one focus; in actuality the orbits differ slightly from ellipses due to perturbations by other celestial bodies.

Any representation of the motion of a celestial body as a mathematical function to be evaluated is termed a *theory*. Because the Moon and planets follow orbits that are in fact nearly circular, the natural ingredients for any theory representing their motions are series of trigonometric functions, similar to Fourier series but more elaborate. The coefficients of the trigonometric terms are usually polynomials in time and functions of other parameters; the trigonometric arguments are themselves functions of time and of parameters describing the orbits of the perturbing bodies.

From the seventeenth century through the present, lunar, planetary, and satellite theories of increasing refinement have been developed. Until the advent of computers, theories were the only means of ephemeris representation. While theories are accurate over comparatively long time spans, all suffer from the limitations of the large amount of time required to evaluate them.

Numerical Integration. The 1960s were a watershed for celestial mechanics and ephemerides: electronic computers became widely available, navigation of spacecraft to the Moon and planets required knowledge of celestial positions with unprecedented accuracy, and the precision and technology of observations increased substantially. The approximations given by analytic lunar and planetary theories usually cannot meet the accuracy requirements of space missions, necessitating the use of numerical integration.

All current high-precision lunar and planetary ephemerides are produced by numerical integration of the differential equations of motion. Even for complex models, the equations can be formulated concisely. The results of the integration are converted and stored as a set of interpolating polynomials. These polynomials can be evaluated at periodic intervals for purposes of printed tabulation (as published annually in many astronomical almanacs throughout the world) or made available to subsequent computer programs for obtaining the positions of celestial bodies at arbitrary times,

Most of the numerically integrated ephemerides in use throughout the world are produced by the Jet Propulsion Laboratory (JPL) of the California Institute of Technology in Pasadena, California. In computer form, JPL ephemerides typically cover a few decades to perhaps a century; DE102, a considerably longer high-precision integrated ephemeris, spans more than 44 centuries, from 1410 B.C. to 3002 A.D. (Newhall *et al.*, 1983).

Mathematical Model

Planetary Ephemerides. The JPL planetary and lunar ephemerides are computed simultaneously by numerical integration. The planetary force model includes contributions from (1) relativistic point-mass interactions of the nine planets, the Sun, and the Moon in the isotropic, parametrized post-Newtonian n-body metric (see Newhall *et* al. [1983] for the equations of motion); (2) the Newtonian effects of nearly 300 asteroids on those same bodies; (3) the interaction of the point-mass Sun on the figures of the Earth and Moon; and (4) the effects of the principal non-spherical gravitational term (J_2) of the Sun on the Moon and planets.

Lunar Ephemeris. Treatment of the lunar ephemeris employs a more extensive model to accommodate the accuracy of laser ranging data. Besides the relativistic point-mass effects the model of the Earth-Moon system includes: (1) interaction of Moon and Sun on the Earth figure; (2) interaction of Earth and Sun on the Moon figure; (3) the effects on the Moon of the Earth solid and ocean tides raised by the Sun and Moon.

In addition to the position of the Moon in its geocentric orbit, the physical libations (the rotational position of the Moon about its center of mass) must be integrated numerically. The libations are represented as a set of three Euler angles defining the orientation of the Moon with respect to the Earth's mean equator and equinox of the epoch J2000: ϕ, the angle along the Earth's equator from the equinox to the ascending node on the Moon>s true equator; θ, the inclination of the Moon's true equator to the Earth's equator; and ψ, the an gle along the Moon's equator from the node on the Earth's equator to the selenographic prime meridian.

The mathematical model for libations represents the response of the Moon to torques arising from action of the point-mass Sun, the point-mass Earth, and the Earth figure on the lunar figure. The lunar moment of inertia is modeled as having a rigid-body component and a time-varying component arising from a delayed dissipative elastic response to the deformation caused by Earth-induced solid tides and by the lunar angular velocity.

Satellite **Ephemerides.** The third area of development of ephemerides involves those of the satellites of Mars and of the giant planets Jupiter through Neptune. (Satellite ephemerides arc not considered in the modeling of planetary and lunar ephemerides. Each of the outer planets and its family of satellites arc treated as if combined into a point mass --- a satisfactory approximation, as the perturbations on other planets due to the actual satellites arc small.)

The ephemerides of Phobos and Deimos, the two satellites of Mars, are represented as theories. The most recent developments arc by Sinclair (1989), based on Earth-based observations and on spacecraft imaging during the Mariner 9 mission in 1971 and the two Viking missions in 1976.

In 1977, two Voyager spacecraft were sent from Earth toward the outer planets. Accurate satellite ephemerides were essential to the success of the missions. Both Voyagers visited Jupiter and Saturn; Voyager 2 continued on past Uranus and Neptune. Up to that time, the ephemerides of outer-planet satellites were determined solely from 1~arth-based telescopic observations. The two missions provided considerable improvement in ephemerides and masses of the satellites.

Unlike the case of planetary and lunar ephemerides, numerical integration of satellite orbits has met with success only for the Uranus and Neptune systems; it has not been used for the G alilean satellites of Jupiter or for the eight principal satellites of Saturn. The numerical integration and parameter estimation procedure fails because of nonlinearities in the satellite systems, arising from (1) the large number of revolutions that occur for the satellites over a given time span, and (2) strong resonances between various satellite pairs. For the planetary and lunar ephemerides, a reasonably linear system, 25 years comprises about 330 revolutions of the Moon and 104 revolutions of Mercury. By contrast, 10, the innermost major satellite of Jupiter, completes nearly 5200 revolutions in 25 years; Mimas, the closest large satellite to Saturn, about 9700 revolutions.

Nonlinearity obstructs integration and estimation as follows: the integration process consists of specifying the position and velocity of each satellite at some initial epoch and then using the equations of motion to propagate the states forward with the integration. In general, any error in the initial states will grow over the span of the integration, yielding a progressively degraded ephemeris. In usual estimation techniques, corrections to the initial states arc made by comparing observations of the satellites with computed values based on the integration and then adjusting the initial conditions accordingly. This technique works only if corrections to the initial states are proportional to measured errors in the orbit (i. e., if the system is linear), not the case for the Jupiter or Saturn systems.

The original theory for the Galilean satellites of Jupiter was developed in the early part of this century by Sampson (1921). Lieske (I 976) at J]'], produced an improved theory of the Galilean satellites using a computer for algebraic manipulation. The theory for the satellites of Saturn used for the Voyager missions was taken from the summary and references found in *Explanatory Supplement* *to the Ephemeris (1961)* and improved by fits to Earth-based and spacecraft observations; a more complete theory is that given by Duriez and Vienne (1991) and continued in Vienne and Duriez (1991).

Construction of the Ephemerides

The JPL ephemerides have been instrumental in the success of NASA planetary and lunar missions. in the early days of unmanned space exploration the ephemerides were derived from planetary and lunar theories. With time, significant advancements in spacecraft tracking systems and data accuracy required analysis beyond the scope of approximations offered by theories and necessitated the use of numerical integration.

Data types. The orbits and other parameters related to the planets are determined by a least-squares fit to various types of observations. The observations span most of the twentieth century (those from earlier times have large uncertainties). The types of observations used are:

Optical meridian transits. The disk of the Sun or a planet is observed through a telescope to cross the meridian. Between 1911 and 1982 the U.S. Naval Observatory in Washington DC made several thousand transit observations of the Sun and Mercury through Neptune. In 1984 the photoelectric meridian transit was introduced, where a photocell replaced the human observer. Transits of Pluto have been obtained since 1988.

Astrolabe. The disk of a planet is observed through a telescope to cross a fixed altitude, both ascending and descending. Observations of Mars through Uranus were begun in 1969. Accuracies are typically from $0\overset{''}{.}3$ to $1\overset{''}{.}6$.

Photographic Astrometry. Before 1988 the observations available for Pluto were from photographic plates. From plate measurements, Pluto's coordinates are established relative to selected reference stars. This data type is also used for planetary satellites other than the Moon.

Satellite Eclipses. Times of disappearance and reappearance of a planetary satellite due to passage through the shadow of its primary are recorded.

occultation Timings. Uranus occasionally passes between the Earth and a star. In 1977 the planet was found to have rings; subsequent measurements of the time and duration of the blocking or occultation of the star's image by the rings give the celestial coordinates of Uranus to less than 0″.2. Similar occultations by the disk of Neptune beginning in 1968 establish Neptune's coordinates to about 0″.3.

Radio Astrometry. Beginning in 1983 the Very Large Array in New Mexico made radio observations of the thermal emission of Jupiter, Saturn, Uranus, and Neptune; the observed celestial coordinates arc accurate to about 0″.03.

Ranges. The above observation types arc measurements of angular position of the designated body as seen on the celestial sphere. Enter the ranging era, in which the measurement is distance between an observing station and a celestial object. Beginning in 1970, Mercury and Venus were ranged by radar, with an uncertainty of about 1.5 km. (By comparison, a typical 1" angular measurement error at Mercury is about 750 km in transverse linear distance.) Ranges to spacecraft in the vicinity of Mercury, Mars, and Jupiter have uncertainties as small as 500 meters.

The Viking landers on Mars were ranged between 1976 and 1982 with uncertainties of 7 meters. Between 1969 and 1972 the Apollo astronauts placed three arrays of laser retroflectors on the lunar surface; a fourth reflector array was landed by the Russian-French Lunakhod 2 spacecraft. Over the following years, more than 8000 laser ranges between terrestrial observatories and the four lunar reflectors were acquired. Lunar ranges since 1990 have uncertainties as small as 2 centimeters or less; both the Viking ranges and the best lunar ranges have relative accuracies of better than 5 parts in 101].

Optical Navigation. Ephemerides of the outer planets and their satellites had errors of 1000 km or more before the Voyager missions. During approach to each planetary system, cameras on board the spacecraft obtained images of the planet and its satellites against a background of catalogued stars. These images were then used to modify the spacecraft trajectory and to refine the satellite c])hc~ncr-ides.

Representation of Ephemerides.

In contrast to printed tabulations, ephemerides used by computers are stored as coefficients of an interpolating polynomial, allowing a user to obtain ephemeris values at arbitrary times. The polynomials of choice for the JPL ephemerides are Chebyshev polynomials (Newhall, 1989). They are stable during interpolation and provide a reliable estimate of the errors introduced due to truncating at a selected polynomial degree. The standard for interpolation error in the JPL ephemerides is 0.5 mm. (This figure denotes the precision to which interpolated values match the original numerical integration, not the actual dynamical state of the solar system.)

Ephemeris Parameter Estimation

Many physical parameters in the solar system can be determined to considerable accuracy from ephemeris data. The creation of the lunar and planetary ephemerides typically entails estimating about 150 parameters, including the initial positions and rates of the planets and Moon, initial values of the lunar libations, station and reflector locations, lunar gravity model, lunar elasticity coefficients, Earth and lunar tidal dissipation, polar motion, the angular position of the Earth (UT]), precession and nutation of the Earth's pole, the astronomical unit (average distance between the Earth and Sun), and the masses of the Moon, planets, and major asteroids. (In practice the actual mass of a celestial body is difficult to determine; the quantity that is well determined and is instead estimated is GM, the product of the gravitational constant G and the mass M of the body.)

A few results from parameter estimation follow:

Relativity. For the Earth-Moon system, laser ranging has provided an accurate confirmation of the Strong Principle of Equivalence (that gravitational mass M_G *is* equal to inertial mass M_I) in the General Theory of Relativity. The formulation used expresses the ratio of the two mass quantities as

$$\frac{M_G}{M_I} = 1 + \eta \frac{U_G}{Mc^2}$$

where η is a dimensionless parameter, U_G *is* **the** gravitational self-energy of the Earth, M *is* the mass of the Earth, and c is the velocity of light. (For the Earth, $U_G/Mc^2 \approx 5 \times 10^{-10}$). By exploiting the fact that a disparity between the two would cause a sunward displacement of the lunar orbit, estimation of the lunar ephemeris has found that, for the Earth,

$$\eta = 0.003 \pm 0.004$$

Some theories of gravity suggest that the gravitation '[constant') G is not constant at all but may be time-varying in some fashion. The usual form in which a variable G is expressed is the ratio G/G. Laser ranging has found that G/G is zero to at least as small as a few parts in 10^{11} per year. Other relativistic quantities are the post-Newtonian parameters measuring curvature and superposition of gravitational fields and geodetic precession of the lunar orbit. All determinations arc consistent with the predictions of general relativity, both from lunar laser ranging and from planetary ranging.

Earth-relatated quantities. Another quantity improved by laser ranging is the effect of the Earth tides on the lunar orbit. The Moon and Sun raise both solid and ocean tides on the Earth, which in turn affect the lunar orbit. The most pronounced effect. is the secular acceleration of the geocentric lunar longitude, whereby the tidal bulge on the Earth lies ahead of the Earth-Moon line and tends to add energy to the lunar orbit. This energy addition causes the average Earth-Moon separation to increase, with an attendant slowing of the Moon in its orbit. The measured acceleration of longitude is - 25.9 arc seconds/century^2, corresponding to the Moon's receding at about 3.8 centimeters/year.

Planetary Gravity. A fruitful use of the ephemerides is the navigation of robotic spacecraft, and the determination of the gravity fields of the Moon and planets. The fine structure of those fields is irregular duc to aspherical mass distribution. The fields are customarily represented by coefficients of spherical harmonics. Precise determination of the trajectories of planet-orbiting spacecraft provides estimations of a large set of gravitational coefficients.

Planetary Masses. ' Any non-orbiting spacecraft passing near a planet or satellite provides a good determination of the body's *GM.* Over the course of the past two decades the GM's of all planets and major satellites (except for the Pluto-Charon system) have been reliably determined from spacecraft data.

Other Ephemeris Applications

Spacecraft Mission Planning. Planned spacecraft missions, particularly to the outer planets and their satellites, face severe navigation constraints, Payload-imposed fuel limitations often necessitate gravitational assists from intermediate planets in order to supply sufficient energy for the spacecraft to reach the target. Sensitivity of the final arrival trajectory to errors at intermediate planets and satellites can be extreme; accurate ephemerides and GM determinations are essential to devising reliable fuel and payload budgets and navigation strategies.

Observations and Data Reduction. Ephemeris accuracy is necessary for acquisition of data such as planetary microwave observation, where angular position is important, and radar ranging, where round-trip travel times must be known *a priori* to within a few microseconds. The reduction of data also demands accurate ephemerides: for the Earth and target body in the case of radar ranging, and for the Earth alone when analyzing the timing of received signals from millisecond pulsars.

Planet X. For several years, some astronomers stated that the best-fit predicted orbit of Uranus differed from the acutal orbit. They attributed this discrepancy to a possible massive tenth planet, designated "Planet X," Several attempts to find it telescopically were made, but without success. Then in 1989 the close approach of Voyager 2 to Neptune provided a significant improvement in that planet's GM. When this new value was included in the numerical integration the Uranus orbit differences largely disappeared, casting substantial doubt on the existence of Planet X.

Summary

Accurate planetary, lunar, and satellite ephemerides are essential for successful space missions. Ephemerides originally were produced from mathematical theories but, with the exception of the satellites of Jupiter and Saturn, are computed by numerical integration. Accurate computation of ephemerides has provided estimates of numerous quantities relating to the planets and satellites and to the theory of relativity.

References

Duriez, L. and A. Vienne, 1991, A General Theory of Motion for the Eight Major Satellites of Saturn. I. Equations and Method of Resolution, *Astron. Astrophys.* 243, 263-275.

Explanatory Supplement to the Ephemeris, 1961, Nautical Almanac Office, U.S. Naval Observatory, Washington, D. C., 362--386.

Lieske, J. H., 1976, Theory of Motion of Jupiter's Galilean Satellites, *Astron. Astrophys.* **56**, 333-352.

Newhall, X. X., 1989, Numerical Representation of Planetary Ephemerides, *Celest. Mech.* 45, 305-310.

Newhall, X. X., E. M. Standish, and J. G. Williams, 1983, DE102: A Numerically Integrated Ephemeris of the Moon and Planets Spanning Forty-four Centuries, *Astron. Astrophys.* **125**, 150-167.

Sampson, R. A., 1921, Theory of the Four Great Satellites of Jupiter, *Mem. Roy. Astron. Soc.* **63**.

Sinclair, A. T., 1989, The Orbits of the Satellites of Mars Determined from Earth-based and Spacecraft Observations, *Astron. Astrophys.* 220, 321-328.

Vienne, A. and L. Duriez, 1991, A General Theory of Motion for the Eight Major Satellites of Saturn. II. Short-period Perturbations, *Astron. Astrophys.* 246, 619-633.

X. X. NEWHALL